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Co-benefits of climate mitigation on air quality and human health in Asian countries

Yang Xie[a,b], Hancheng Dai[c,*], Xinghan Xu[d], Shinichiro Fujimori[b,d], Tomoko Hasegawa[b], Kan Yi[e], Toshihiko Masui[b], Gakuji Kurata[d]

[a] School of Economics and Management, Beihang University, Beijing 100191, China
[b] Center for Social and Environmental Systems Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba-City, Ibaraki 305-8506, Japan
[c] College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China
[d] Department of Environmental Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8540, Japan
[e] College of Urban and Environmental Sciences, Peking University, Beijing 100871, China

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ABSTRACT

Climate change mitigation involves reducing fossil fuel consumption and greenhouse gas emissions, which is expensive, particularly under stringent mitigation targets. The co-benefits of reducing air pollutants and improving human health are often ignored, but can play significant roles in decision-making. In this study, we quantified the co-benefits of climate change mitigation on ambient air quality and human health in both physical and monetary terms with a particular focus on Asia, where air quality will likely be degraded in the next few decades if mitigation measures are not undertaken. We used an integrated assessment framework that incorporated economic, air chemistry transport, and health assessment models. Air pollution reduction through climate change mitigation under the 2 °C goal could reduce premature deaths in Asia by 0.79 million (95% confidence interval: 0.75–1.8 million) by 2050. This co-benefit is equivalent to a life value savings of approximately 2.8 trillion United States dollars (USD) (6% of the gross domestic product [GDP]), which is decidedly more than the climate mitigation cost (840 billion USD, 2% of GDP). At the national level, India has the highest potential net benefit of 1.4 trillion USD, followed by China (330 billion USD) and Japan (68 billion USD). Furthermore, in most Asian countries, per capita GDP gain and life value savings would increase with per capita GDP increasing. We robustly confirmed this qualitative conclusion under several socioeconomic and exposure-response function assumptions.

1. Introduction

The majority of countries around the world have made greenhouse gas (GHG) reduction targets and submitted them to the Paris Agreement. However, policymakers generally hesitate to set more ambitious mitigation targets because climate mitigation carries economic costs, and the more ambitious the mitigation target, the higher the cost. Many studies have suggested that air pollution improvement and climate mitigation carry significant co-benefits. (Balbus et al., 2014) estimated that by 2020, reductions in adverse health outcomes due to decreased fine particulate matter ($PM_{2.5}$) exposure would save the United States 6–30 billion USD (in 2008 USD). West et al. (2013a, b) found that a representative concentration pathway 4.5 (RCP 4.5)-equivalent GHG mitigation would result in 0.5 ± 0.2, 1.3 ± 0.5, and 2.2 ± 0.8 million fewer premature deaths globally in 2030, 2050, and 2100, respectively. The co-benefit of per ton of carbon dioxide (CO_2) reduction is about 50–380 USD for the worldwide average, 30–600 USD for the United States and Western Europe, 70–840 USD for China, and 20–400 USD for India. The economic co-benefits are much higher in East Asia than in other regions such as U.S. and EU, approximately 10–70 times the marginal cost in 2030. McCollum et al. (2013) found that carbon reduction efforts could reduce energy-related health impacts by upwards of 2–32 million fewer disability-adjusted life years globally in 2030. A study in the United States showed that climate mitigation could prevent more than 10,000 premature deaths in 2050 and 5000 deaths in 2100 due to air quality improvement, equivalent to a value of statistical life (VSL) of approximately 150 billion USD and 1.3 trillion USD (in 2005 USD) by 2050 and 2100, respectively (Garcia-Menendez et al., 2015). Yang and Teng found that if China reduces its 2005 carbon emissions intensity by 60–65%, compared to 2010 levels, sulfur dioxide, nitrogen oxide, and $PM_{2.5}$ emissions will be reduced by 78.85%, 77.56%, and 83.32%, respectively, by 2030 (Yang and Teng,

* Corresponding author at: Room 246, Environmental Building, College of Environmental Sciences and Engineering, Peking University, Beijing 100871, China.
E-mail address: dai.hancheng@pku.edu.cn (H. Dai).

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2017). One study from OECD shows the global economic costs of outdoor air pollution increase to 1% of global GDP by 2060, with highest GDP losses in China (Lanzi et al., 2018).

When evaluating the economic costs of climate mitigation, it is necessary to include the potential societal benefits to more comprehensively assess the costs and benefits of various mitigation goals. Health improvement constitutes a substantial fraction of the potential benefits, along with averted adaptation costs and residual damage. Quantifying the co-benefits of climate mitigation may convince policymakers and the public to formulate integrated mitigation strategies and to adjust their lifestyles toward a green and low-carbon society (R. Xie et al., 2016). However, future GHG and air pollutant emissions are highly dependent on socioeconomic conditions and climate mitigation targets, the former of which are highly uncertain, and the latter of which are quite relevant to policy intervention. To address such uncertainties, the climate research community has made tremendous strides in developing the next generation of scenarios for climate change research (Moss et al., 2010) including shared socioeconomic pathways (SSPs) and RCPs. SSPs are stylized projections of future energy consumption and emissions that consider the challenges of vulnerabilities, adaptation, and mitigation (Kriegler et al., 2014; Fujimori et al., 2016; van Vuuren et al., 2017), whereas RCPs are a set of four new pathways developed for the climate modeling community as a basis for long-term and near-term modeling experiments (van Vuuren et al., 2012). One study in EU also found positive effect related to health can offset the resource costs associated to the clean air policy, which resulted in positive macroeconomic impacts for the economy (Vrontisi et al., 2016).

Previous studies have focused on the air quality and health benefits of climate mitigation at the aggregate global level or in developed countries such as the United States under certain socioeconomic pathways and mitigation targets. However, without consistent assumptions on socioeconomic pathways or mitigation targets, it is difficult to consistently compare the costs and benefits among various studies, which may confuse policymakers. To avoid such confusion and inconsistencies, new simulations and assessments are needed that consider the latest progress in climate scenario development such as SSPs and RCPs. Furthermore, air pollution and its impacts are less severe in developed countries than in developing countries; thus more attention should be given to emerging developing countries, particularly Asia, where several of the most populous and dynamic developing countries are located. Asian countries suffer serious negative health impacts of air pollution due to rapid economic growth and fossil energy consumption in recent decades, particularly $PM_{2.5}$ and tropospheric ozone pollution in China and India (Lelieveld et al., 2015; Rohde and Muller, 2015; Ghude et al., 2016). One study by the World Health Organization (WHO) showed that the global mortality due to air pollution exceeded 6.5 million in 2015, more than half of what occurred in Asia (Landrigan et al., 2017). Thus, Asian countries are key players and contributors in guaranteeing the success of global climate mitigation (Calvin et al., 2012; Paltsev et al., 2012).

However, few studies have investigated air quality and health benefits in Asian countries. Moreover, a limitation of most existing studies is that they typically adopted a one-way assessment; air pollutant emissions from the economic system deteriorate air quality, causing adverse health impacts, and policy interventions will ease these negative impacts through the chain, and are defined as benefits. However, the feedback effects of adverse and improved health impacts on the economic system are not reflected in such approaches. Based on this premise, we selected Asian countries as target regions, and SSP2 combined with the 3.4 W/m^2 forcing target in 2100 as representative climate scenarios. We aimed to distinguish the costs and benefits of climate mitigation moving toward 2050 in Asia. Moreover, we adopted a novel methodology that closes the economy-environment-health-economy loop by combining an air chemistry transport model, an economic model, and a health assessment model to account for the complex interactions among the environment, human health, and economic systems. Our study also provides sensitivity analyses under alternative socioeconomic conditions.

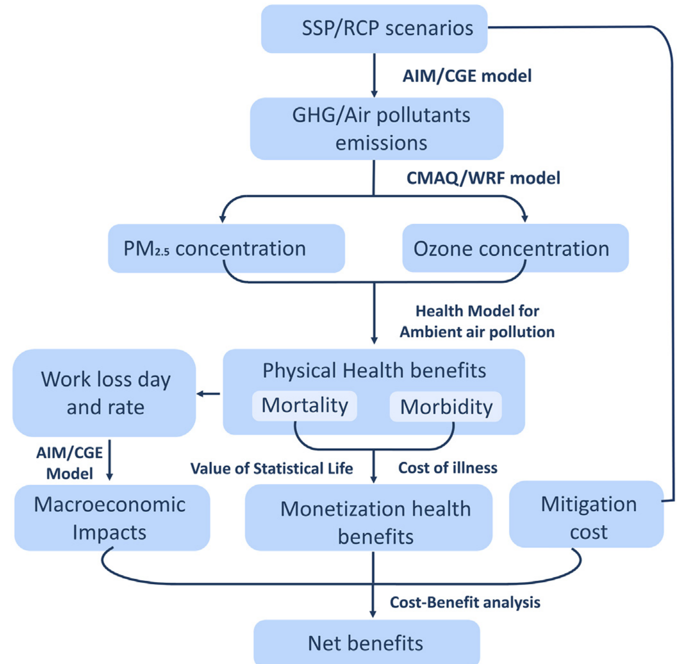

Fig. 1. Research framework.

2. Methodology

We combined the Community Multiscale Air Quality (CMAQ) model, a health assessment model, and the Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) model to evaluate the long-term health and economic impacts caused by ambient $PM_{2.5}$ and ozone pollution under different climate mitigation and SSP2 scenarios in Asian countries (Fig. 1). Emissions data is taken from the SSP database generated by the AIM/CGE model (Fujimori, Hasegawa et al., 2017; Fujimori et al., 2016) and downscaled to a 0.5° grid (Fujimori, Abe et al. 2017). Based on the gridded emissions data, the CMAQ model simulated the annual average $PM_{2.5}$ and daily 8 h maximum ozone concentrations in 2005 and 2050. The health assessment model quantified health impacts due to outdoor air pollution, which are categorized as morbidity and mortality and monetized as additional medical expenditures and VSL. Furthermore, health impacts due to mortality and morbidity were converted into per capita work time loss, which was used as a change in the labor participation rate in the AIM/CGE model to identify macroeconomic impacts. Finally, cost-benefit analyses were conducted to determine the net benefit of climate mitigation in different regions of Asia. The per capita benefit is from net co-benefit dividing the total population in each country. This methodological framework was developed in our previous studies on China (Y. Xie et al., 2016, Wu et al., 2017, Tian et al., 2018) and extended to all of Asia in this study.

2.1. AIM/CGE global model

The AIM/CGE global model is a multi-regional, multi-sectoral, and multi-gas recursive dynamic CGE model (described in detail in Fujimori et al., 2012; Fujimori et al., 2016; and Masui et al., 2010) (Masui et al., 2010; Fujimori et al., 2016; Fujimori, Abe et al. 2017; Fujimori, Hasegawa et al., 2017). This model was developed to analyze energy, land use, agriculture, emissions, and climate policy at the global level, with a primary focus on Asian regions. The roles of the AIM/CGE model

in this study are as follows: to evaluate the economic impact of climate mitigation, to provide future air pollutant emissions for the air quality model, and to provide future socioeconomic pathways (e.g., per capita GDP) that are used to monetize the health impacts. In this study, we conducted simulations from 2005 to 2050 with a 1-year time step. Further introduction to this model is presented in the Supplementary information basic assumption.

2.2. Health impact assessment model

The health model quantified air pollution-related mortality, morbidity, work time loss, health expenditures, and VSL. The health impact assessment model integrated several exposure-response functions (ERFs) from global epidemiological studies that assume linear relationships between $PM_{2.5}$ and ozone concentrations and health responses. As showed in Eqs. (1) and (2), when the concentrations of $PM_{2.5}$ and daily 8 h maximum ozone lower than the threshold value of 10 μg/m^3 (Pope III et al., 2002) and 70 μg/m^3 (Turner et al., 2016), respectively, RR is 1, which causes no health impacts. Linear function assumes that the concentration-response function (CRF) is a constant, the values of which could be found in Table A1 for ozone and Table A2 for $PM_{2.5}$ in the appendix. The number of health endpoints is estimated by multiplying RR with population and reported cause-specific mortality rate (Eq. (2)).

On the other hand, different monetization methods are used to monetize the physical mortality and morbidity cases. Monetary value of morbidity is indicated by additional health expenditure, which is obtained by multiplying outpatient and hospital admission price with total endpoints (Eq. (6)). The price is a function of per capita GDP of each province (Eq. (7)), and the parameters β, θ are estimated through regression analysis of statistical price by disease and GDP of each province from 2003 to 2012. Furthermore, mortality cases were monetized with the VSL (Eq. (8)), which is the marginal rate of substitution between individual's wealth and micro mortality risk reductions (Hammitt, 2000). VSL is an important indicator to compare with the mitigation cost. We chose different VSL results from Xie (2011), and adopted the method developed by the OECD (2016) to modify the VSL from different countries in the future. We used the VSL from China, 2.3 million Chinese yuan renminbi (CNY) (2016 value; 95% CI: 1.5–3.5 million), to conduct sensitivity analyses (Jin, 2017). The total annual work loss days (WLDs) of a region is the sum of the WLD due to mortality and the cumulative WLD from chronic morbidity in the population aged 30–65 years (Eq. (3)). The 2013 Global Burden of Disease Study provided age-specific all-cause mortality data from 1979, 1990, and 2010. The mortality among 30–64-year-olds at those time points was approximately 25%, 26%, and 29%, respectively, of the total all-cause mortality. We assumed 30–65-year-olds accounted for 27% of the total chronic mortality, the average assumption of the 2010 Global Burden of Disease Study. The annual per capita work loss rate (WLR) was obtained by dividing the WLD by the working population and annual working days (Eq. (4)). In the CGE model, WLR was used to calculate the actual labor force after subtracting the work loss (Eq. (5)). The population over 65 years and under 15 years of age were not included in the labor force, and their health impact only contributed to additional health expenditures.

$$RR_{p,r,s,y,m,e,g}(\mathrm{C}) = \begin{cases} 1, \quad C_{p,r,s,y} \le C0_p \\ 1 + CRF_{m,e,g} \times (C_{p,r,s,y} - C0_p), \text{ linear function}, C_{p,r,s,y} > C0_p \\ 1 + \alpha(1 - exp(-\gamma(C_{p,r,s,y} - C0_p)^{\delta})), \text{ nonlinear function}, \mathrm{C}_{p,r,s,y} > C0_p \end{cases} \tag{1}$$

$$EP_{p,r,s,y,m,e,g} = \begin{cases} P_{r,y,m} \times (RR_{p,r,s,y,m,e,g}(C) - 1), \text{ for } linear \text{ morbidity } function \\ P_{r,y,m} \times I_{r,\text{"}all\ cause\text{"}} \times (RR_{p,r,s,y,m,e,g}(C) - 1), \text{ for } linear\ mortal \\ P_{r,y,m} \times \hat{I}_{r,e} \times (RR_{p,r,s,y,m,e,g}(C) - 1), \text{ for non}linear\ mortality\ function, \text{ where } \hat{I}_{r,e} = \frac{I_{r,e}}{RRr,e} \end{cases} \tag{2}$$

$$WLD_{p,r,s,y,v} = \sum_{m}(EP_{p,r,s,y,m,\text{"wld"},v}) + \sum_{e,y'<y}(EP_{p,r,s,y',\text{"mt"},e,v}) \times SHR_{r,\text{"}15-65\text{"}} \times DPY \tag{3}$$

$$WLR_{p,r,s,y,v} = \frac{WLD_{p,r,s,y,v}}{DPY \times P_{r,y,\text{"}15-65\text{"}}} \tag{4}$$

$$LAB_{p,r,s,y,v} = LAB0_{r,\text{"ref"},y} \times (1 - WLR_{p,r,s,y,v}) \tag{5}$$

$$HE_{p,r,s,y,m,e,v} = PR_{r,s,y,e,v} \times EP_{p,r,s,y,m,e,v} \tag{6}$$

$$PR_{r,s,y,e,v} = \beta_{r,e} \times GDPPC_{r,s,y} + \theta_{r,e} \tag{7}$$

$$VSL_{p,r,s,y,e} = WTP_{r,y,e} \times EP_{p,r,s,y,m,e,v} \times \left(\frac{GDP_{r,y}}{GDP_{\text{"China"},\text{"}2010\text{"}}}\right)^{0.5} \tag{8}$$

where:

$RR(C)$ Relative risk for endpoint at concentration C [case/person/year or day/person/year]
EP Health endpoint [case/year or day/year]
C The concentration level of pollutant
$C0$ Threshold concentration that causes health impacts (10 μg/m^3 for $PM_{2.5}$ and 70 μg/m^3 for ozone.)
CRF Concentration-response function
P Population, aged 15–65 for work loss day
$I_{r,\text{"all cause"}}$ The reported average annual natural death rate for endpoint
WLD Annual work loss day [day/year]
WLR Annual per capita work loss rate
$SHR_{r,\text{"}15-65\text{"}}$ The share of mortality between 15 and 65 years old due to ambient air pollution, equal to 0.27 based on (Wang et al., 2012)
LAB Labor force after considering work loss
LAB0 The labor force in the reference scenario
DPY Per capita annual working days (5 day/week ∗ 52 week/year = 260 day/year)
HE Total additional health expenditure [billion USD/year]
PR Price of medical service [USD/case]
$GDPPC_{r,\ s,\ y}$ Per capita Gross Domestic Production from CGE model
$\beta_{r,\ e}$, $\theta_{r,\ e}$ Parameters derived from regression analysis of medical service price
$VSL_{p,\ r,\ s,\ y,\ e}$ Value of health endpoint
$WTP_{r,\ y,\ e}$ Willingness to pay for avoiding premature death and morbidity
Suffix p, pollutant; r, region; s, scenario; y, year; m, mortality or morbidity; e, endpoint; g, value range; "*wld*," "work loss days" subset of e; "*mt*," "chronic mortality" subset of m.

2.3. CMAQ model

The CMAQ model is an atmospheric dispersion model developed by the United States Environmental Protection Agency (US EPA) to address regional air pollution problems (Ching and Byun, 1999). We used the CMAQ version 5.0.1 model to calculate pollutant concentrations. Meteorological data were provided by the Weather Research and Forecasting (WRF) model (Zhang et al., 2014). The WRF is a meso-scale meteorological model developed by the National Oceanic and

Table 1
Scenarios of climate mitigation and air quality benefits.

Scenario	Climate mitigation target in 2100 radiative forcing	Air pollution effects
BL_NO	None	Not considered
BL_AP	None	Considered
MT_NO	3.4 W/m^2	Not considered
MT_AP	3.4 W/m^2	Considered

Atmospheric Administration that simulates physical processes in the atmosphere. It is a numerical weather prediction system designed to serve both atmospheric research and operational forecasting needs. For the WRF (version 3.4.1) model we used the National Centers for Environmental Prediction-Final global re-analysis data as the meteorological input data, and used the 2013 data for all of the simulation years, which provided a 6 h temporal global analysis data in a 1° grid. The Sparse Matrix Operator Kernel Emissions system, which was developed by the US EPA and has been maintained by the Carolina Environmental Program of the University of North Carolina, was used to develop the emissions processing system. We used the WRF/CMAQ model to simulate annual average $PM_{2.5}$ and daily maximum 8 h average surface ozone concentrations in Asian countries. The geographical resolution was 80 km × 80 km grids covering mainland Asia, converted from 0.5° gridded emissions information provided by AIM/CGE using the CB05 chemical module in CMAQ. The time pattern for emissions was based on (Woo et al., 2012).

2.4. Scenarios

This study evaluated three dimensions (Table 1): climate mitigation, socioeconomic conditions, and the health impacts of air pollution. For the socioeconomic conditions dimension, of the five SSPs in the integrated assessment models community (Kriegler et al., 2014), SSP2 ("middle of the road") was chosen to analyze the co-benefits of socioeconomic transition (Fujimori, Hasegawa et al., 2017; Rao et al., 2017) in this study, and SSP3 ("regional rivalry") was used for the sensitivity analysis. Regarding climate mitigation dimension, because the 2.6 W/m^2 goal, which is often interpreted as 2 °C, was unattainable in scenario SSP3 due to the challenges of climate change mitigation (O'Neill et al., 2014; Riahi et al., 2017), the 3.4 W/m^2 emissions pathway was selected instead, which is still an achievable global mean temperature change compared to the pre-industrial level, 2.0 °C at the end of century, with an approximately 50% chance. The dimension of the impact of air pollution on health was only used for economic assessment in the AIM/CGE model. Two paired options were set up, with (_AP in Table 1) and without (_NO) considering air pollution-related health impacts on the economy. The "without consideration" option assumed that there were no economic impacts from air pollution, a non-existent situation; however, the role of this scenario was to act as a benchmark for comparison with the other scenarios to evaluate the negative impacts of pollution and the benefits of pollution reduction. Based on these three dimensions, four scenarios were established (Table 1). By comparing these scenarios, the following information was expected: by comparing the BL_AP and MT_AP scenarios, we could determine the cost of climate mitigation; and by comparing the MT_NO and MT_AP scenarios, we could quantify the macroeconomic benefits under SSP2 and climate mitigation.

3. Results

3.1. Air pollutant emissions and concentrations

Climate change mitigation aims to limit global mean temperature increase to 2 °C or less at the end of this century (Fig. A11 in Supplementary information). Climate mitigation involves not only reducing carbon emissions (Fig. A13), but also reducing air pollutant emissions (Figs. A18–A26). Reducing air pollutants will improve air quality. Fig. 2 shows the annual average $PM_{2.5}$ (top) and daily 8 h maximum ozone concentration (bottom) in the BL_NO scenario in 2005 and concentration changes under different scenarios. For $PM_{2.5}$, the noticeably polluted areas in 2005 were the central and eastern parts of China, the Korean peninsula, eastern Russia, southern Japan, India, Malaysia, and Indonesia. In 2050, the $PM_{2.5}$ concentrations (Fig. 2b) in

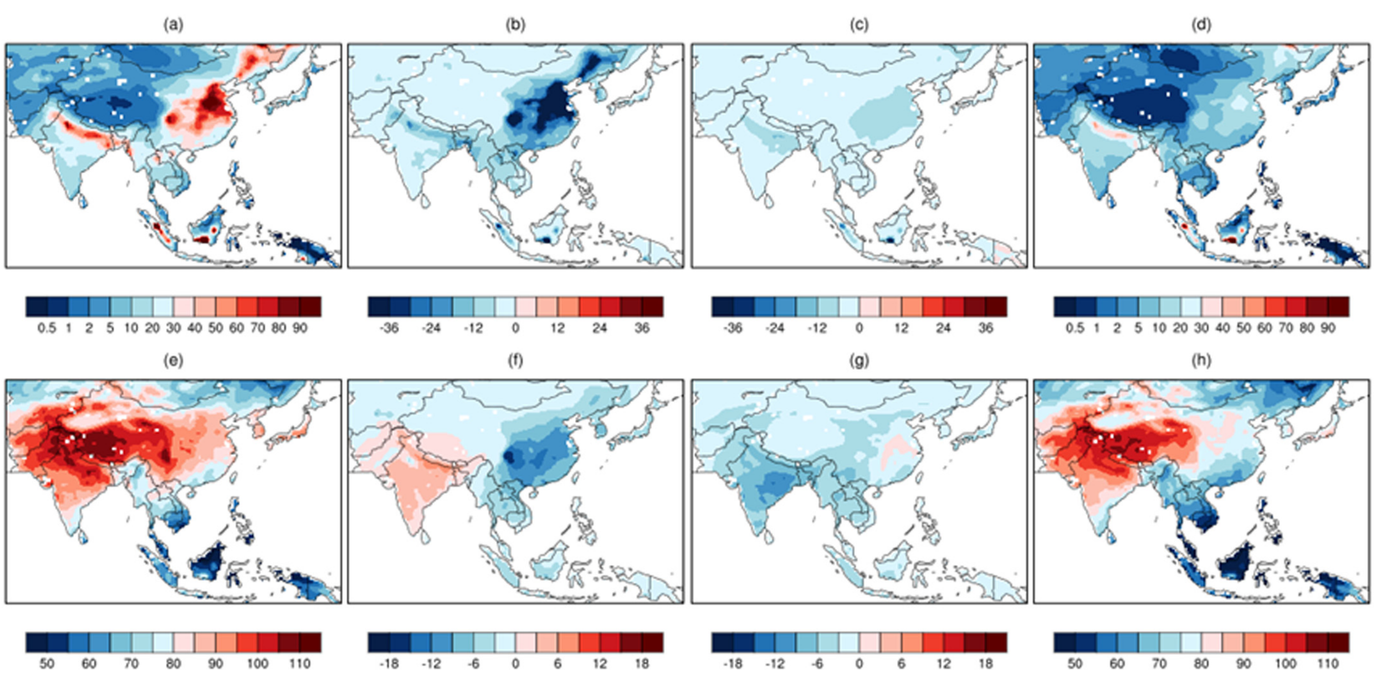

Fig. 2. Concentrations and concentration changes in $PM_{2.5}$ (top) and ozone (bottom) in Asia. (a) $PM_{2.5}$ and (e) ozone concentrations in 2005; (b) $PM_{2.5}$ and (f) ozone concentration changes from 2005 to 2050 in the BL_AP scenario due to socioeconomic development; (c) $PM_{2.5}$ and (g) ozone concentration changes from the BL_NO to the MT_AP scenario in 2050 due to climate mitigation; (d) $PM_{2.5}$ and (h) ozone concentrations in 2050 in the MT_AP scenario.

India and China will further increase in the BL_NO scenario, particularly in northern India where the increasing $PM_{2.5}$ levels will reach more than 50 μg/m^3 compared to 2005. By contrast, in other parts of Asia, except for southern Indonesia, the $PM_{2.5}$ concentration will decrease over time due to decreased primary air pollutants emissions. Fig. 2c shows that climate mitigation can significantly reduce $PM_{2.5}$ concentrations in the MT_AP scenario. For eastern China and northern India, the $PM_{2.5}$ concentration reduction was approximately 30 μg/m^3, which was much greater than that in other regions of Asia.

The ozone concentration change among the different scenarios was not significant. Fig. 2e shows the daily 8 h maximum ozone concentration in 2005. The ozone concentrations were higher in northeastern India and southwestern China, likely due to high levels of natural background in the Qinghai-Tibet Plateau. However, these areas have lower population density, particularly China; thus it was not a serious public health problem. By contrast, in the most urbanized area of the northern part of Asia, the daily 8 h maximum ozone concentration was above 80 μg/m^3, which is higher than the WHO health assessment standard (70 μg/m^3). Ozone pollution leads to adverse health outcomes. In most parts of southern Asia, ozone concentrations were lower than 70 μg/m^3. From 2005 to 2050 (Fig. 2f), modeled increases in ozone concentration were the most remarkable in India and China as a result of socioeconomic changes in the BL_AP scenario. In most parts of India, ozone will increase by more than 30 μg/m^3 in the north and 10 μg/m^3 in the south, whereas in China, ozone concentration will be reduced by about 5 μg/m^3 in the densely populated areas. Fig. 2g shows that climate mitigation will have diverse effects on ozone pollution in 2050. In all parts of India and most parts of southern Asia, ozone concentrations will decrease, whereas the concentrations will increase in the central and eastern parts of China even under climate mitigation. Fig. 2h shows the ozone concentrations in the MT_AP scenario in 2050. The ozone concentrations remain high in the western and central parts of China.

3.2. Impacts on mortality and VSL

The most concerning impact of exposure to air pollutants is premature death. The total mortality from both $PM_{2.5}$ and ozone pollution in Asia was 3.3 million in 2005 (Fig. 3), which accounted for the majority of the global outdoor air pollution-related mortality, compared to the WHO estimate of 3.7 million in 2012, highlighting the importance and need for paying more attention to Asian regions, a goal of this study (Héroux et al., 2015). In 2005, the total mortality in China was estimated to be 1.7 million, with 1.4 million from $PM_{2.5}$ exposure and 0.29 million from ozone exposure. In India, the total mortality was 1.1 million, with 0.73 million from $PM_{2.5}$ and 0.40 million from ozone exposure. Our estimates of $PM_{2.5}$ for India and China were quite similar to the 2015 IEA report (IEA, 2016), approximately 1.2 million and 0.6 million, respectively. By contrast, in Japan, mortality was much lower than in China and India, at approximately 0.04 million in 2005. The mortality rates were about 0.24 million and 0.14 million, respectively, for the rest of South and Southeast Asia. By 2050, the total mortality in Asia due to air pollution will decrease slightly. However, in India, mortality will increase by about 25% compared to 2005 levels in the BL_NO scenario, due to poor air quality and population growth. In China, mortality will significantly decrease due to reductions in air pollutants emissions due to baseline air quality legislation assumptions (Rao et al., 2017). It is worth noting that socioeconomic effect from SSP3 to SSP2 contributes to a significant reduction in mortality in China due to various factors such as optimizing its industrial structure, development of renewable energy, and adoption of air pollution control technologies. In Japan, the mortality reduction will also be significant because the exposure population is decreasing. For the rest of South and Southeast Asia and the rest of Asia, mortality will be 0.24 million and 0.23 million in 2050 according to the BL_AP scenario. Compared to the BL_NO scenario, the avoided mortality for all of Asia from climate mitigation is predicted to be 0.79 million in 2050 in the MT_AP scenario. This study also estimated the economic benefits from avoided premature deaths (Table A5). The life value savings in Asia are approximately 1.7 trillion USD (3% of GDP). India has the largest number of avoided premature deaths (0.46 million) from climate mitigation, a life value savings of approximately 720 billion USD (7% of GDP). China has a relatively high number of avoided premature deaths (0.22 million), for a life value savings of approximately 720 billion USD (3% of GDP). The amount of avoided premature deaths in other Asian countries is much lower than in India and China.

3.3. Impact on morbidity and expenditures

Fig. 4 shows the impact of ambient air pollution on morbidity in Asia. Per capita morbidity refers to the probability of an individual experiencing an air pollution-related health endpoint over the course of 1 year, including outpatient and hospital admission. The results revealed that in all of Asia in 2005, the per capita adverse health effects of air pollution in terms of morbidity risk were about 29% per year. In 2050, morbidity risk will decrease to 27% according to the BL_AP scenario and to 20% according to the MT_AP scenario. The trend in China is similar to the trend in Asia as a whole. The morbidity risk was 30% in 2005 and will reduce quite significantly to 13% in the BL_AP scenario and further reduce to 11% in the MT_AP scenario in 2050. India had the highest air pollution-related morbidity risk rate in Asia for a long-term period, at approximately 40% in 2005. In the BL_AP scenario, the morbidity risk will increase to 45% in 2050, whereas in the MT_AP scenario it will decrease to 32%. In Japan, the morbidity risk was 32% in 2005, and will decrease to 25% in 2050 in the BL_AP scenario, and 20% in the MT_AP scenario. Japan has a relatively higher morbidity risk owing to its aging population, as the elderly are more sensitive to air pollution. For other Asian countries, the morbidity risk from air pollution is lower than in Japan, China, and India, at approximately 26% in 2005, and 30% in the BL_AP scenario and 20% in the MT_AP scenario in 2050. Climate mitigation could reduce the morbidity risk in all Asian countries. In the rest of South Asia and Southeast Asia, morbidity risk is much lower, and the benefit from climate mitigation is lower, than in other Asian regions.

Air pollution also leads to additional medical expenditures (Table 1). In 2005, the total additional medical expenditures related to air pollution in all of Asia amounted to 13 billion USD. China (5.5 billion USD) and India (3.5 billion USD) accounted for the majority of the total expenditures, followed by Japan (1.7 billion USD) and the rest of South and Southeast Asia (1.4 billion USD). By 2050, as the per capita GDP and income increase, the total medical expenditures will grow significantly, particularly in developing regions, although morbidity will decrease in some cases due to air quality improvement. For example, health expenditures due to air pollution in Asia in 2050 will reach approximately 44 billion USD in the BL_AP scenario and 32 billion USD in the MT_AP scenario. At the regional level, China's total health expenditure will be 13 billion USD in the BL_AP scenario and 9.1 billion USD in the MT_AP scenario. India's total health expenditure will be approximately 22 billion USD in the BL_AP scenario and 15 billion USD in the MT_AP scenario. Compared to the BL_NO scenario, climate mitigation in the MT_AP scenario could reduce expenditures by 12 billion USD in Asia, 3.6 billion USD in China, 6.5 billion USD in India, 0.33 billion USD in Japan, 1.1 billion USD in the rest of South and Southeast Asia, and 0.61 billion USD in the rest of Asia in 2050 (Table 2).

3.4. Work time loss and economic impacts

Air pollution also causes work time loss due to both mortality and morbidity. In 2005, the annual per capita work time loss in Asia (Fig. 5) was 4.3 h, whereas in 2050, work time loss will be approximately 2.5 h in the BL_AP scenario and 1.7 h in the MT_AP scenario. At the regional

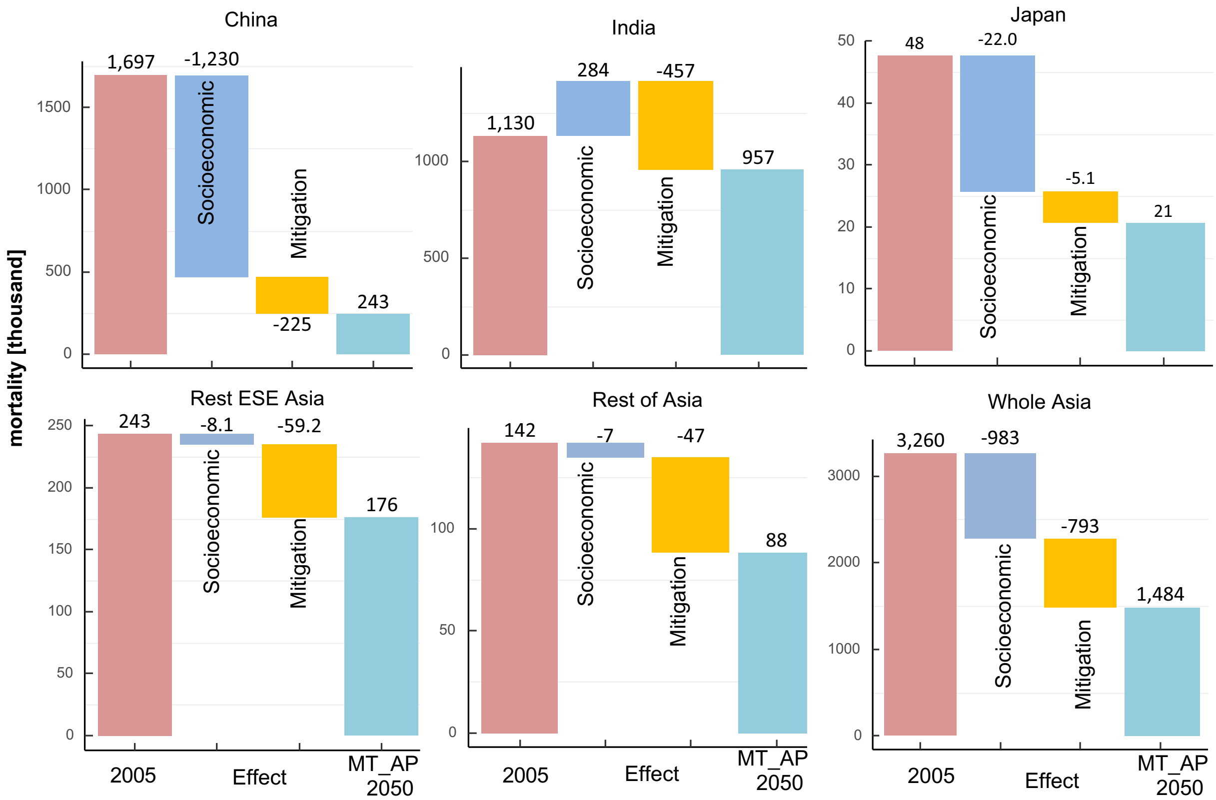

Fig. 3. Mortality due to $PM_{2.5}$ and ozone pollution in 2005 and 2050. The socioeconomic effects represent any changes in socioeconomic assumptions from 2005 to 2050 (e.g., population, gross domestic product, technology, and legislation). The mitigation effects are the differences between scenarios with and without climate change mitigation. MT_AP, the results of climate change mitigation in 2050; Rest ESE Asia, the rest of Southeast Asia.

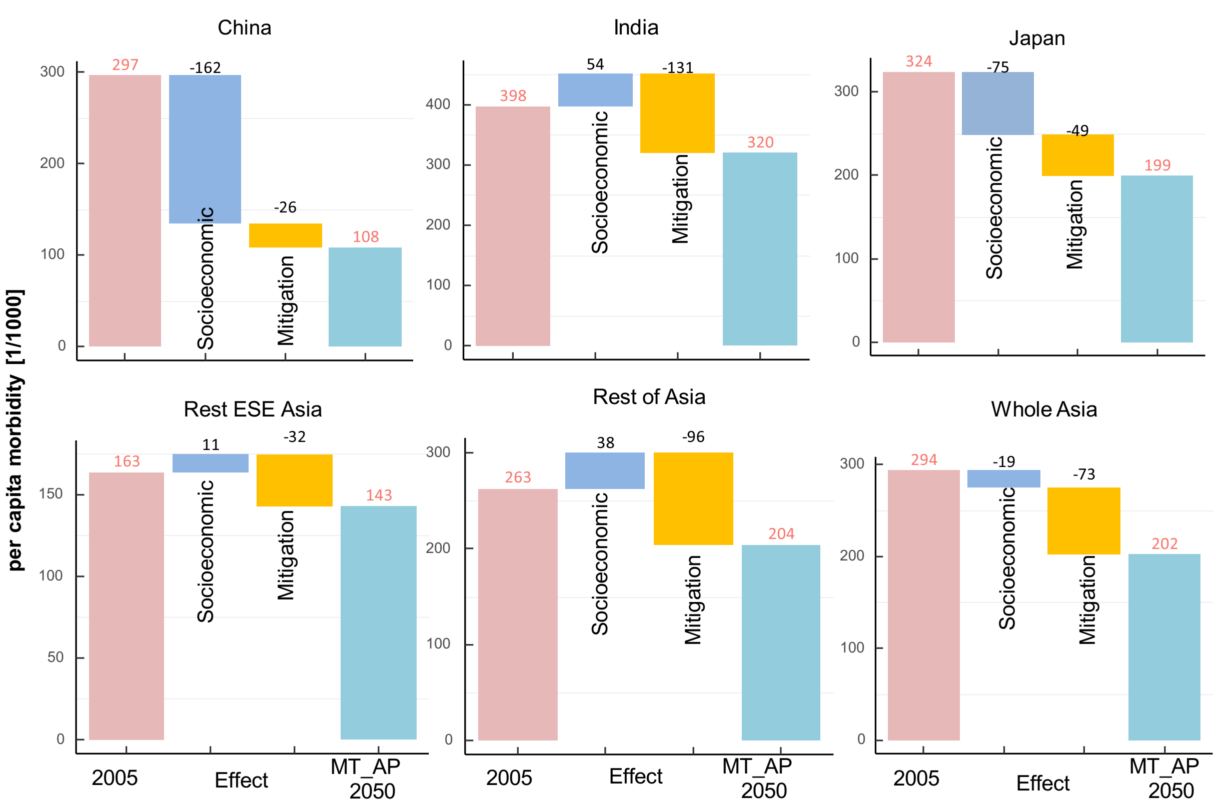

Fig. 4. Morbidity risk due to $PM_{2.5}$ and ozone pollution in Asian countries. The socioeconomic effects represent any changes in socioeconomic assumptions from 2005 to 2050 (e.g., population, GDP, technology, and legislation). The mitigation effects are the differences between scenarios with and without climate change mitigation. MT_AP, the results of climate change mitigation in 2050; Rest ESE Asia, the rest of Southeast Asia.

Table 2
Health expenditures due to air pollution-related diseases (unit: billion USD).

Scenario	Year	China	India	Japan	Rest ESE Asia	Rest of Asia	Whole Asia
BL_NO	2005	5.5	3.5	1.7	1.4	0.4	12.5
BL_NO	2050	12.7	21.8	1.7	5.8	1.9	43.8
MT_AP	2050	9.1	15.3	1.3	4.6	1.3	31.7

Rest ESE Asia, rest of Southeast Asia.

level, the annual per capita work time loss in 2050 will be 8.8 h (0.42% of total annual work time in 2005) and 3.4 h (0.16%) in the BL_AP scenario in China, 6.1 (0.29%) and 2.06 h (0.26%) in India, 1.4 and 1.2 h in Japan, and 2.7 and 1.6 h in the rest of Asia, respectively. Under climate mitigation scenario MT_AP, per capita work time loss drops back to 2.0 h in China, 3.8 h in India, 1.0 h in Japan, and 1.1 h in the rest of Asia in 2050. In 2005, China had the highest work time loss, whereas in 2050 India will replace China with the highest work time loss. It is worth noting here that although the socioeconomic transition from SSP2 to SSP3 helps to reduce mortality and morbidity in India (Figs. 3 and 4), per capita work loss is even lower in SSP3. This is mainly because the age coverage of mortality (over 30 years old) and morbidity (all age groups) is different from that of the labor force (15–65 years old). Japan had the lowest work time loss from air pollution, and the work time loss in the rest of Asia was lower than that in China and India, but higher than that in Japan.

Fig. 6 shows the relationship between per capita GDP and per capita benefits from climate mitigation in Asian countries including GDP gain, VSL gain, and expense gain. In most Asian countries, when the per capita GDP increases, per capita GDP gain and VSL gain also increase. However, per capita expenditure savings are not significantly correlated with per capita GDP. Conversely, in Japan, the per capita GDP gain and expenditure savings decrease as per capita GDP increases, whereas the per capita VSL does not change, which is quite different from the trends in other countries in Asia. Our results show that developing countries in Asia experience greater per capita gain from climate mitigation than developed countries.

4. Discussion

4.1. Cost-benefit analysis

The main results of this analysis indicate that climate mitigation entails co-benefits in air quality in the MT_AP scenario in all Asian countries, and greater reductions in $PM_{2.5}$ but lesser reductions in ozone. These reductions could prevent 0.79 million premature deaths, save 30 billion USD in health expenditures, and provide a 170 billion USD economic benefit from an increased labor supply in 2050. Unsurprisingly, climate mitigation also incurs additional economic costs. Fig. 7 provides a comprehensive cost-benefit analysis of climate mitigation from the perspective of air pollution-related health impacts. Here, we used the GDP loss from climate mitigation policy estimated by the CGE model as the mitigation cost. By contrast, the mitigation benefit comprises many aspects related to air quality improvement, including GDP gain due to increased labor supply, as simulated by the CGE model; health expenditure savings due to reductions in morbidity, as calculated by the cost of illness method in the health assessment model; reduction in VSL due to decreased mortality, as estimated by the willingness to pay method; and the net benefits of the aforementioned costs and benefits. Evidently, the net benefit from climate mitigation is positive in Asia as a whole, as well as in most countries shown in the figures. The climate mitigation cost in Asia in 2050 is 840 billion USD (or 1.8% of GDP). However, the benefit is approximately three times the mitigation cost. This decisive point indicates that climate mitigation

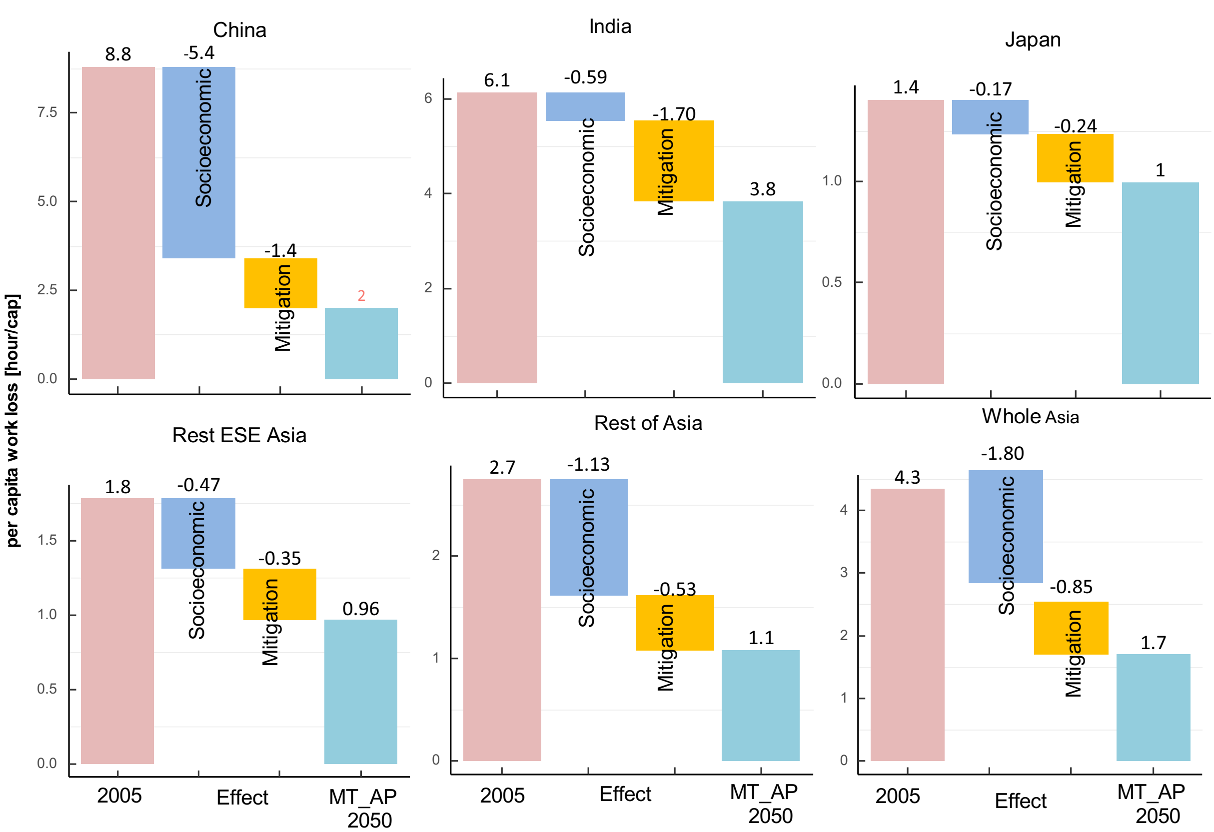

Fig. 5. Work time loss in Asia due to air pollution. The socioeconomic effects represent any socioeconomic assumption changes from 2005 to 2050 (e.g., population, GDP, technology, and legislation). The mitigation effects are the differences between the scenarios with and without climate change mitigation. MT_AP, the results of climate change mitigation in 2050; Rest ESE Asia, the rest of Southeast Asia.

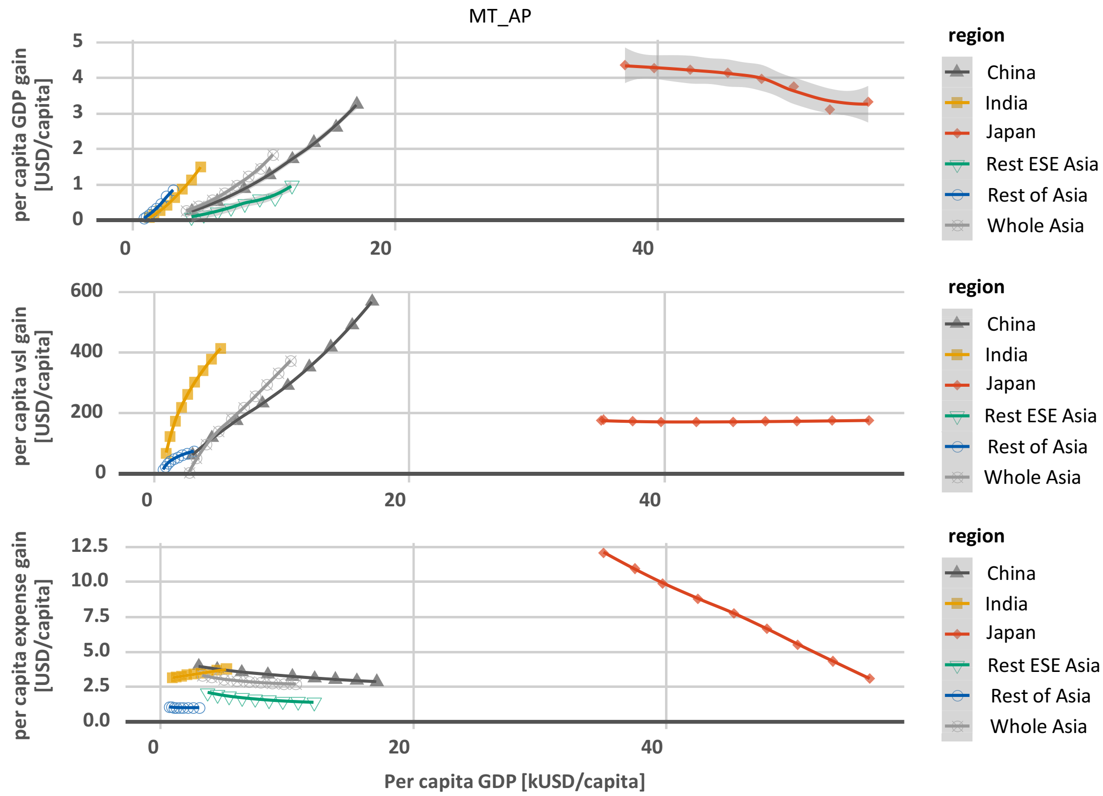

Fig. 6. The economic impacts of air pollution in Asian countries. The x-axis represents per capita GDP. Y-axis represents the economic gain from climate mitigation. Top panel: per capita GDP gain due to increased work time and labor income; middle panel: per capita value of a statistical life (VSL) gain; bottom panel: per capita expenditure gain.

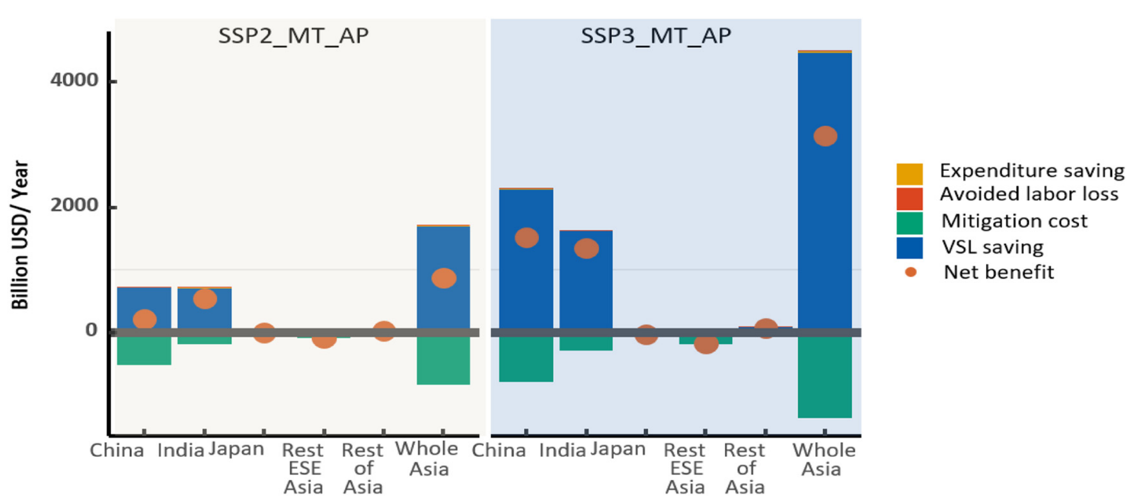

Fig. 7. Cost-benefit analysis of climate mitigation under SSP2 and SSP3 socioeconomic conditions in Asian countries. (Note: MT_AP is changed to SSP2_MT_AP for better comparison.)

is worthwhile even when considering the co-benefit of health improvement alone. Further analysis showed that the benefits are dominated by VSL savings that far exceed the benefits in GDP gain and health expenditure savings, which was consistent with many other studies (West et al., 2013a, b; Thurston and Bell, 2014; Garcia-Menendez et al., 2015; Saari et al., 2015).

A closer look at the regional level revealed that China had the highest climate mitigation cost, due to a large amount of existing carbon emissions and pressures of emission reduction in the future. Nevertheless, the benefits from climate mitigation in China could outweigh the costs. In 2050, the climate mitigation cost in China will amount to 510 billion USD (equivalent to 4.8% of GDP), which accounts for 61% of the total mitigation costs in Asia. Meanwhile, climate change mitigation can prevent 0.22 million premature deaths in China, equivalent to a VSL of 780 billion USD, which is about 1.5 times the GDP loss associated with climate change mitigation. Regarding India, its industrialization processes and economic development behind China by one to two decades, while its population is increasing faster than that of China, which indicates that India will be the next major energy consumer and producer of GHG emissions. Hence, India's air quality will be severely worse than that of China in 2050 in the baseline scenario, as will the negative health impacts of air pollution. This also

indicates that India will experience higher potential benefits of climate mitigation. Fig. 7 shows that the avoided VSL loss in India is 1.5 trillion USD (3.0% of GDP) in the MT_AP scenario, which is about eight times the mitigation cost (190 billion USD), and the ratio is much higher than that of China. Although the mitigation cost is relatively high and the benefit is lower in Japan, the benefit remains higher than the mitigation cost. Interestingly, the net benefit to the rest of East and Southeast Asia is negative, likely because these countries are surrounded by ocean and their air quality is better than that of China and India, even under the baseline scenario. Hence, climate mitigation will provide less additional improvements in air quality and health. However, this does not mean that climate mitigation is a pure burden for these countries, as the benefits may lie in other areas such as saved adaptation costs and coastal damage avoided. For the rest of Asia, the benefit/cost ratio is higher than that of Japan but lower than that of China and India. When we compare the per capita gain from climate mitigation with per capita GDP among Asian countries, developing countries in Asia could receive more benefits from climate mitigation.

4.2. Sensitivity analyses

Sensitivity analyses were performed with regards to two aspects: socioeconomic conditions of SSP3, as shown in the right panel in Fig. 7, and using the 95% confidence intervals of the ERF (Table A4) and the VSL (Table A5) in the health model. Compared with SSP3, SSP2 has lower energy consumption and population increases much lower. SSP2 also has higher health investment and access to health facilities. Less exposed population and lower air pollutants concentration under SSP2 will lead to lower health impact than SSP3. At the same time, mitigation cost under SSP2 is also lower than SSP3. Our results show mitigation co-benefit is also lower under SSP2. Changing socioeconomic conditions to SSP3 did not alter the main findings of this study, namely, the net benefits of climate mitigation are positive for Asia and for most individual countries except for the rest of East and Southeast Asia. Nonetheless, there were several remarkable differences. First, the mitigation cost in SSP3 was higher than in SSP2, by about 1.4 trillion USD. This was understandable, as the baseline emissions level in SSP3 were the highest among all the SSPs. Society must pay higher costs to bring the emissions level down to the target. Second, the benefit/cost ratio in SSP3 was higher than that in SSP2. The benefit was approximately 4.2 times the cost in SSP3. This is because more emissions must be reduced from the SSP3 baseline than from the SSP2 baseline to reach the 3.4 W/m^2 target; consequently, the health benefits are larger. China's benefits exceeded India's because the SSP3 baseline emissions of China were higher. We used the latest VSL from a Beijing study to show the uncertainty of assigning life values (Table A5). The results indicated that the uncertainty from VSL was much greater than that from the ERFs. We used the 95% CIs from the ERFs and VSL to perform the uncertainty analysis. First, from the ERFs, the mortality rate in Asia in 2050 was predicted as 0.4–4.2 million in the SSP2_BL_AP scenario, and 0.3–2.7 million in the SSP2_MT_AP scenario. At the same time, the life value savings from climate mitigation were 0.7–5.8 trillion USD in the SSP2_MT_AP scenario and 1.0–9.0 trillion USD in the SSP2_BL_AP scenario. We chose a VSL of 1.5–3.5 million CNY to carry out the uncertainty analysis. The life value savings in Asia was 3.2–7.4 trillion USD in the SSP2_MT_AP scenario and 7.0–16.3 trillion USD in the SSP2_BL_AP scenario. The uncertainty from different VSLs was much larger than the uncertainty from different ERFs. At the same time, the uncertainty under SSP3 was much higher than under SSP2 (Tables A4 and A5). Even using different VSLs with a large uncertainty rate, the benefit was still much greater than the mitigation cost. Thus our overall conclusion remained unchanged.

4.3. Policy implications

The most important policy implication from this study was the robust finding that air pollution co-benefits could pay for the climate change mitigation cost of attaining the 2 °C goal in most Asian countries. Moreover, that implication held for both SSP2 and SSP3 variation. This indicates that policymakers should not hesitate any longer regarding the cost of climate mitigation; instead, they should be more proactive in cutting GHG emissions. The co-benefits of climate stabilization produced by avoiding negative impacts in various sectors could potentially be even greater. China and India have very large populations; thus, climate change mitigation would bring higher benefits. In Asia, the potential benefit is approximately 7–10% of GDP. The benefit would be approximately 1.5–7% of GDP in China and 17–24% in India. These two countries would experience the greatest benefits. Another policy implication is related to the fact that the mitigation cost of SSP3 is higher than that of SSP2. Although the benefit/cost ratio is higher in the SSP3 scenario, it is not advisable that society should move in the SSP3 direction, because it involves higher pollution and is less sustainable. Instead, the developing countries in Asia should take early action and make plans to transform their economies toward SSP2, which is more sustainable. One positive sign is that the Chinese government is currently emphasizing restructuring its industrial structure under various slogans such as "Green and Low-carbon Transformation," "Ecological Civilization," and so forth We hope that with the transformative experiences gathered in the next decades, China will lead other emerging countries to avoid long-term lock-in, particularly the closest follower, India.

4.4. Limitations

This study had many limitations that require further improvement and investigation. The first is the coverage of the benefit. Climate mitigation not only has benefits on air pollution reduction and human health, but also on other aspects such as adaptation and avoided adverse impacts, which are likely to be important for the Southeast Asian countries in our study. This will be an interesting topic for future study. Second, for the human health impact assessment, we only accounted for impacts on the labor supply, whereas other studies have indicated that air quality may also affect labor productivity. However, there is no ERF to quantify the impact on labor productivity. If we can quantify productivity change in the future, the benefits of climate change mitigation will be higher than our current estimation, but our overall conclusion will still hold if we consider productivity impact. Third, we only quantified the health impacts related to ambient air pollution and ignored the impacts of indoor air pollution, which are also quite significant. To avoid complexity, we did not create a full simulation of SSP1–5 or other more ambitious but more concerning climate targets such as the 2.6 W/m^2 equivalent (Van Vuuren et al., 2011) or even more stringent ones. In addition, we only simulated the situation in 2050; therefore, the temporal features of the benefit/cost ratio are still unknown. Further studies are needed to provide more comprehensive policy insights. If we consider the feedback from health improvement, it might have the additional positive impact on the economy. However, our approach is not able to estimate this impact so far.

5. Conclusions

In this study, we quantified the health and economic co-benefits of air quality improvements in both $PM_{2.5}$ and ozone for achieving the 2 °C climate mitigation goal in Asia. This study provides a relatively detailed cost-benefit analysis of climate mitigation policy in Asia by comparing the monetized health benefits with the mitigation cost. The methodology adopted is novel in that it includes the feedback effects of human health impacts on the economy, thereby closing the economy-environment-health interaction loop. We found that the benefits from air quality and health improvement could offset the total costs of climate mitigation in Asia. Our findings are in accordance with previous studies in that the overall benefits of climate mitigation far exceed the

mitigation costs in Asia. Although the benefit/cost ratio varies among individual Asian countries, the general benefit is much higher than the mitigation cost. We also compared the per capita gain from climate mitigation and per capita GDP in Asian countries and found that in developing countries, when per capita GDP increases, the per capita gain from mitigation will also increase. Through assessing the limitations of this study, we identified several potentially important future directions of cost-benefit analysis in climate policy, including adding more elements of co-benefits in the analytical framework and uncovering the benefit/cost features over a longer timeframe and under various socioeconomic and mitigation targets.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.07.008.

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